Rain Contribution to Oceanic and Terrestrial Water Balance

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1. Atmospheric water balance

The equation of water balance in the atmospheric column is

$$\frac{\partial W}{\partial t} + \nabla \cdot \mathbf{\Theta} = E - P = F \qquad (1)$$

where

$$\Theta = \int_0^{p_s} q\mathbf{u}dp \qquad (2)$$

is the moisture transport integrated over the depth of the atmosphere, and

$$W = \frac{1}{g}\int_0^{p_s} qdp \qquad (3)$$

is the precipitable water or column integrated water vapor. In these equations, p is the pressure, p_s is the pressure at the surface, q and **u** are the specific humidity and wind vector at a certain level. Bold symbols represent vector quantities. For period longer than a few days (residence time of water in atmosphere), P = E- $\nabla \cdot \mathbf{\Theta}$.

Over ocean

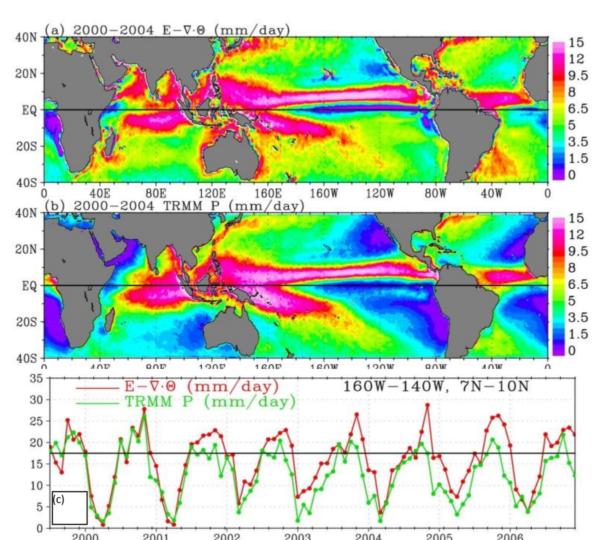

Fig. 1 Annual mean of (a) E-$\nabla \cdot \Theta$ and (b) P in mm/day, averaged from 2000-2004, derived from QuikSCAT, SSM/I, and TMI. (c) Monthly mean time series of E-$\nabla \cdot \Theta$ and P averaged between 160W-140W and 7N-10N.

Over land

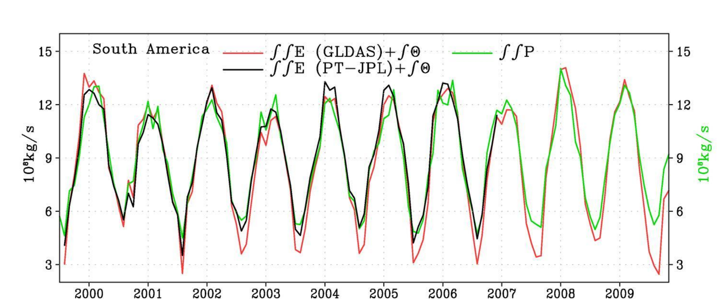

Fig. 2 Monthly mean of E (GLDAS CLM)+∫Θ (red), E (PT-JPL)+∫Θ (black), compared with P (green) from TRMM 3B42, integrated over South America. Two sets of E are used, one from model output, GDLAS (red), and the other derived from satellite data, PT-JPL (black).

TRMM data demonstrate near closure of atmospheric water balance over tropical ocean and land. GPM will provide global coverage and improvement over land. E over land is being improved with soil moisture measured by new L-band sensors.

2. Mass balance

Over global oceans, the sum of all river discharge from land (R) is balanced by the time change of mass (∂M/∂t) and surface water flux (F), integrated over all ocean area.

$$\int R = \iint \left(\frac{\partial M}{\partial t} + F\right) \qquad (4)$$

where ∫ and ∬ represent line and area integrals, respectively. Similarly, over a continent or an river basin

$$\int R = -\left(\iint \left(\frac{\partial M}{\partial t} + F\right)\right) \qquad (5)$$

where M is the mass of the continent or the river drainage basin and E is the evapotranspiration over land.

Over ocean

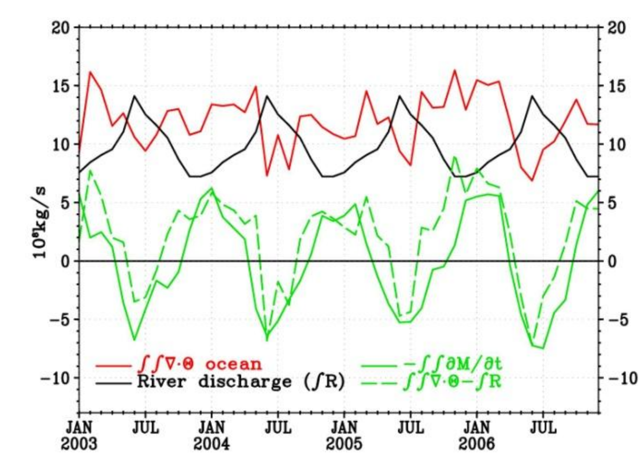

Fig. 3 Monthly mean of mass change rate ∬-∂M/∂t (solid green line) from GRACE, freshwater flux ∬$\nabla \cdot \Theta$ (red line), sum of climatological total river discharge across all coastline ∫R (solid black line) from Dai and Trendberth (2002), and ∬$\nabla \cdot \Theta$-∫R (dashed green line) over the global ocean.

Over land

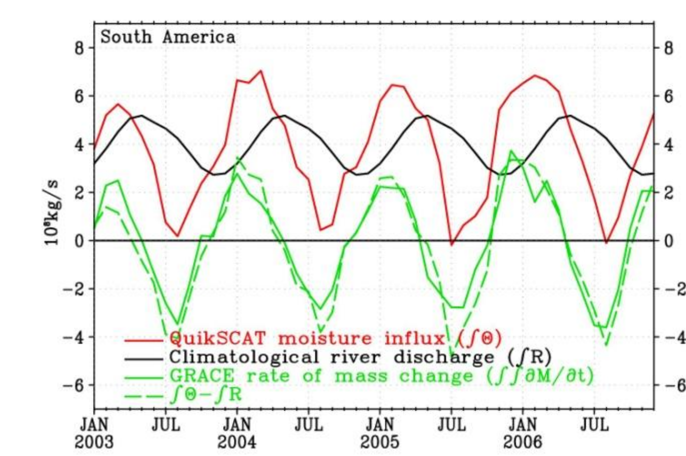

Fig. 4 Monthly mean of mass change rate ∬∂M/∂t (solid green line), climatological river discharge ∫R (solid black line), total moisture transport across coastline into the continent ∫Θ (red line), and ∫Θ-∫R (dashed green line) over South America.

Fig. 3 shows that, over global ocean, the difference between F and R agrees with ∂M/∂t both in magnitude and in phase of annual variation, for the four-year period. The difference between **−**∂M/∂t and $\nabla \cdot$**Θ−**∫R has a mean of 2.1**x**10^8 kg/s and a standard deviation of 2.6**x**10^8 kg/s. The standard deviation is 18% of the peak-to-peak variation of 12 **x**10^8 kg/s. Over the continent of South American (Fig. 4), ∫**Θ**-∫R agrees, both in phase and in magnitude, with ∬∂M/∂t. The standard deviation of the difference is 0.9 x10^8 kg/s, which is 7 % of the peak-to-peak variation of 13 x10^8 kg/s.

3. Amplification of water cycle, expansion of Hadley cell, and change in atmospheric river under global warming

Three hypotheses:

(1) Wet region gets wetter and dry region gets drier

(2) Hadley cell expansion

The poleward boundaries of the Hadley cell are defined as the boundary between easterly and westerly winds and between positive and negative E-P.

(3) Atmospheric river intensifies

We describe atmospheric river using Θ.

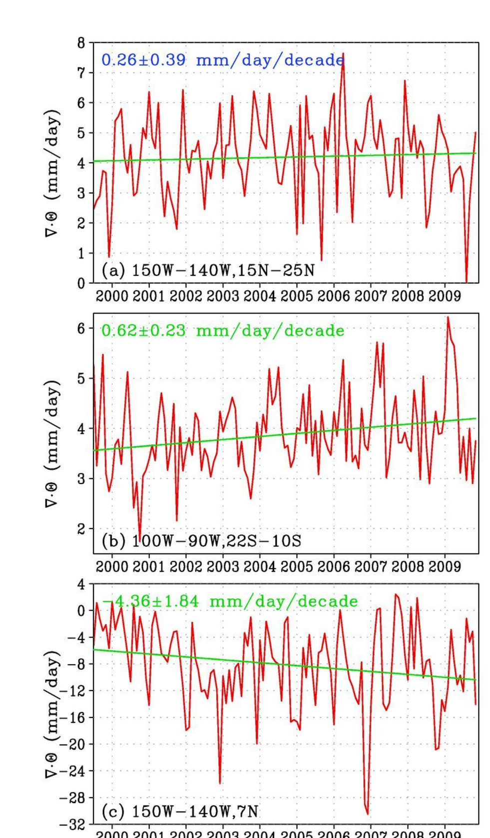

Fig. 5 Time series of $\nabla \cdot \Theta$ averaged over (a) 150ºW-140ºW, 15ºN-25ºN, (b) 100ºW-90ºW, 22ºS-10ºS, and (c) 150ºW-140ºW, 7ºN. Linear slope (green line) and standard error of the slope are marked at the top, with green color above and blue color below the 95% confidence level.

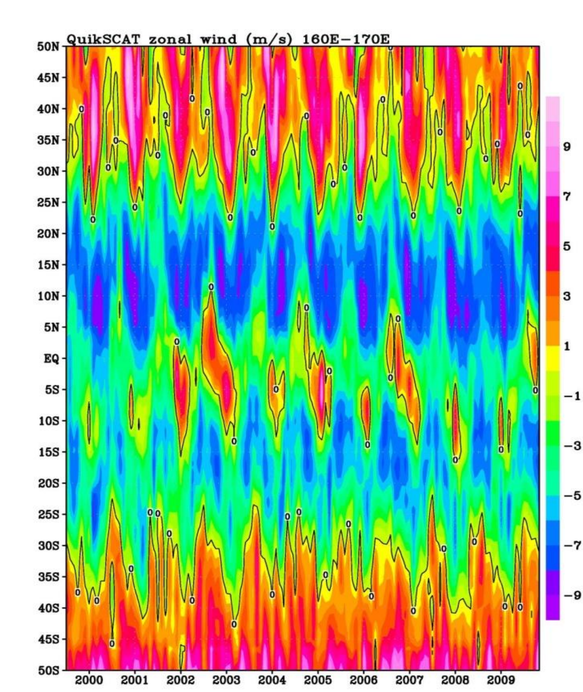

Fig. 6 Hovmoller diagram of zonal component of ENW observed by QuikSCAT averaged between 160ºE-170ºW.

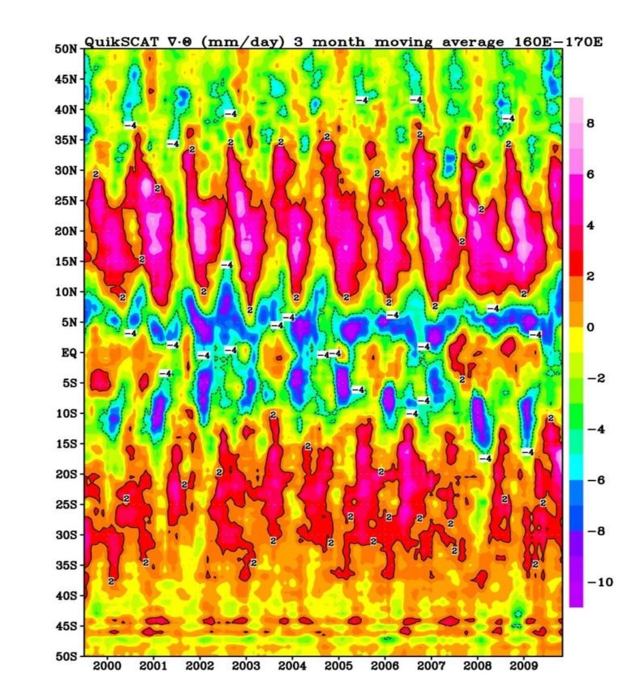

Fig. 7 Same as Fig. 6, except for -$\nabla \cdot \Theta$. A 3-month moving average is applied.

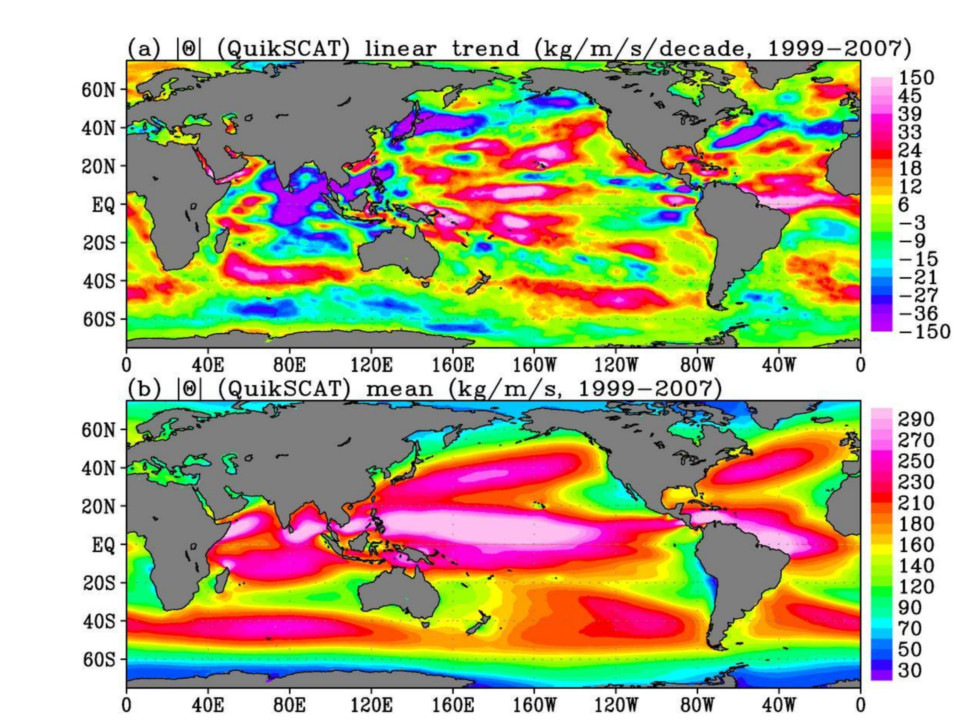

Fig. 8 Linear trend of magnitude of Θ (a), and mean of Θ for period 1999-2009. High magnitude of Θ in North Pacific and North Atlantic are referred to as the atmospheric river that has strong North America and European rainfall. They show positive trend in the past decade.

Regional uncertainties exist. More accurate data are needed.